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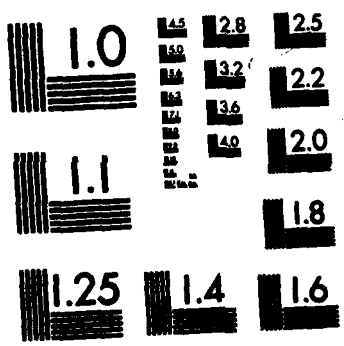

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University of Illinois at Urbana-Champaign

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S-C-R Compatibility and Dual Task Performance in Two Complex Information Processing Tasks: Threat Evaluation and Fault Diagnosis

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This experiment was conducted to extend the principles of stimulus central-processing/response or S-C-R compatibility, described in an earlier report by Sandry and Wickens, to a more complex environment. The principle states that tasks with verbal central-processing demands will be best served by voice input and output channels. Tasks with spatial demands will be best served by visual/manual channels. A verbal task requiring subjects to proceed through a hierarchical checklist of systems and components to ascertain their

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) status (fault), is time-shared with a spatial task, requiring subjects to evaluate the relative velocity vector of two aircrafts for the likelihood of interception. In different conditions each of these were served by both input and output modalities, in single and dual task configurations.

The general results indicated that anticipated compatibility effects were obtained and often enhanced under dual task conditions. In particular, in some circumstances compatibility effects dominated those of resource competition. That is, performance on both tasks in a dual task pair was better when they shared a common input channel, but were both S-C compatible, than when they shared different channels, but one was incompatibly displayed. The practical implications of these results to the interfacing of tasks with voice recognition and synthesis technology are discussed.

Introduction

In previous reports (Wickens, Vidulich, Sandry, & Schiflett, 1981; Sandry & Wickens, 1982; Vidulich & Wickens, 1982), we have introduced the concept of stimulus/central-processing/response compatibility, or S-C-R compatibility as an important factor to consider when implementing voice recognition and synthesis technology. The S-C-R compatibiity concept is an extension to more complex tasks of the principle of S-R compatibility. According to this principle, certain response assignments are most compatibly mapped to certain stimulus configurations. These assignments are sometimes defined in terms of spatial configurations (Fitts & Seeger, 1953; Simon, 1969; Cotton, Tzeng, & Hardyck, 1980), and sometimes in terms of stimulus and response modalities (Brainaird, Irby, Fitts, & Alluisi, 1962; Greenwald, 1979) in which auditory input is found to be most compatibly mapped to speech responses and visual inputs most compatible with manuall responses.

The concept of S-C-R compatibility expands upon the S-R compatibility principle by incorporating the mediating central processing code of a task (Posner, 1978). We assert that tasks can be defined in terms of the extent to which their central processing operations (transformations, rehearsal) depend upon spatial versus verbal working memory (Baddeley & Hitch, 1974). Within the framework of this dichotomy, spatial working memory is that in which analog continuous gradations in stimulus properties are important to be preserved in working memory because these are ultimately important for response. In verbal working memory the information is represented in a more abstract, symbolic, arbitrary format, involving primarily words, or linguistic structures. Tasks using spatial codes of central processing would be those involved in navigation, monitoring, or controlling of analog dynamics, or working within the dimensional structure of a complex data base. Those involving verbal processing would be those requiring the memory of words, and logical operations such as troubleshooting.

If such a dichotomy is feasible, then we propose that tasks that are predominantly verbal in their central processing demands will be best served by auditory input and speech response (S-C and C-R compatible, respectively). Tasks that are predominantly spatial on the other hand will be S-C and C-R compatible with visual input and manuall responses, respectively.

The justification for these assertions is based upon a combination of logical analysis and experimental results. Thus verbal tasks are assumed to be S-C compatible with auditory input because the acoustic code is the dominant code of verbal working memory (Conrad, 1964; Crowder, 1978). A speech input is congruent with this code. Furthermore, several studies have shown that verbal material is better retained when input is auditory rather than visual (e.g., Nilsson , Ohlsson, & Ronnberg, 1977; Murdock, 1968). Spatial tasks are assumed to be S-C compatible with visual rather than input because of the high spatial bandwidth of the visual system, and its greater resolution of information concerning the three euclidian dimensions of space.

With regard to output, verbal tasks are compatible with speech output to the extent that there is a natural mapping of words in working memory to words in the response. Translating words to manuall keypresses requires an extra, usually abitrary transformation. Spatial tasks are more compatible with manuall responses because of the lifetime's experience that the hands have gained in exercising precise and continuous analog continuous control. The voice is of course capable of generating continuous modulation, but this is along a dimension (pitch), that is not isomorphic with the spatial axes of translation and rotation.

When S-C compatibility is examined in more detail it is apparent within the framework of the multiple resources model (Wickens, 1980), that there are in fact four, rather than two alternate formats of information display. Either auditory or visual input can be presented in either verbal or spatial codes. Figure 1 presents these four formats, along with the two alternative codes of central processing. The arrows associate what we propose to be the most compatible formats with the appropriate central processing codes. For each central processing code, the possible compatibility ordering of the remaining three display formats is less well defined. Consider for example, a task with central processing demands that are spatial. If for some reason, the most compatible visual spatial display cannot be employed, will a more compatible mapping be realized with a display of the same code but different modality (an auditory-spatial display, using analog dimensions of pitch and apparent localization), a display of a different code but the same modality (visual-verbal, i.e., print), or even a display differing in both modality and code (i.e., speech).

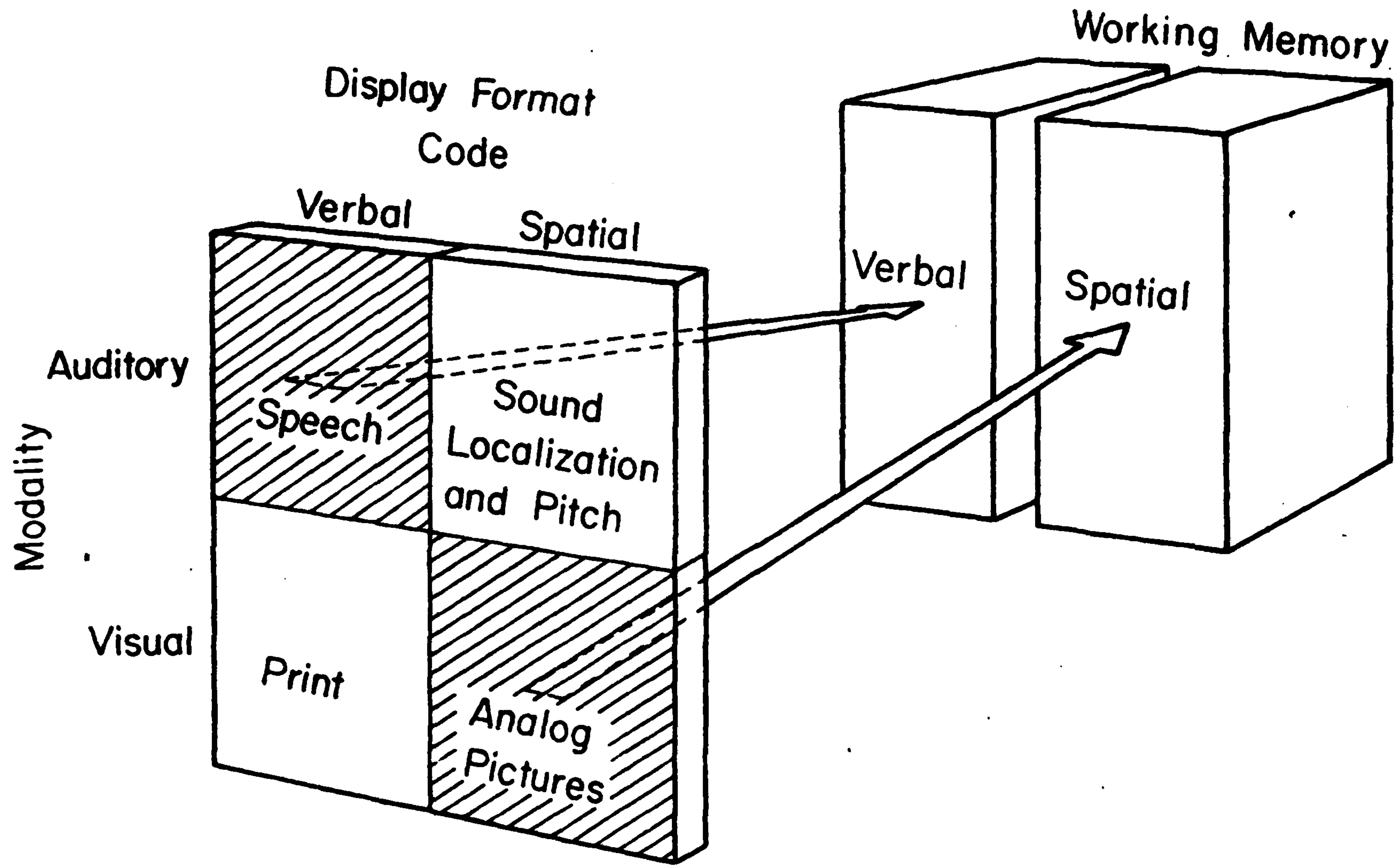

Figure 1: Optimal assignment of display formats to central processing codes.

We argue that such choices among less compatible formats should be *dictated in part by the criterion of avoiding resource competition* between concurrent activities. Thus in the preceding example, if the relevant spatial information were to be conveyed in an environment with high visual workload, then an auditory-spatial format would be favored.

The preceding discussion emphasizes that in multi-task environments, compatibility effects cannot be considered in isolation of resource competition. The joint consideration of compatibility and resource competition suggest two general principles that were supported by an investigation by Sandry and Wickens (1982). (1) The relative advantage of compatible mappings (or the disadvantage of incompatible mappings) will be enhanced as dual task loading increases. (2) There are circumstances in which compatibility may "tradeoff" with resource competition. For example, in a multi-task environment that is already heavily visual, it is not clear whether it will be better to display information concerning an additional spatial task in a compatible visual format (high compatibiity but high resource competition), or in an auditory format (lower compatibility but low resource competition). Such a tradeoff will of course depend upon the relative importance of the two competing variables.

Two investigations in our laboratory have provided some tentative support for the S-C-R compatibility concept and its relation to dual task performance. Vidulich and Wickens (1981) measured performance on a Sternberg memory search task with all four input/output modality combinations. In this study we found that single task error rate on this verbal task varied significantly across conditions in the direction predicted by the compatibility principle. Highest error rate was obtained in the V/M condition, lowest in the A/S condition, with the two mapings sharing 1 compatible and 1 incompatible assignment (VS and AM), showing an intermediate error rate. Sandry and Wickens (1982) investigated S-C-R compatibility in a more complex environment with both spatial and verbal side tasks, each interfaced with all four i/o combinations. The spatial task involved acquisition of a target whose identity was specified after the trial began. The verbal task required memorization of alpha-numeric information. Both tasks were performed by themselves, and concurrently with a simulated flight task requiring negotiation of an air corridor in a FA-18 mock-up simulator. For both of the side tasks, both the auditory and visual inputs were also verbal (i.e., speech or print). As a consequence, S-C compatibility was in the optimal format for the verbal side task, but not for the spatial task which would have been better served with a visual spatial input. Despite this fact, the results consistently supported the predictions of S-C-R compatibility. Performance for the spatial task was best, and task interference least with the visual input and manuall response. Performance with the verbal task was best with auditory input and speech response. Compatibility effects were also enhanced by increases in flight task difficulty.

Based upon the encouraging results of these investigations, the intent of the current study is to explore and extend the concept of S-C-R compatibility in two directions: increasing task complexity and unconfounding resource competition from compatibility. (1) Both of the side tasks used by Sandry and Wickens were relatively simple ones. The verbal task required only maintaining a string of six alpha-numeric characters in working memory, while the spatial task involved identifying and locating a target in space--demanding only modest central processing requirements. The present experiment employs two tasks with more complex central processing requirements that are designed to extend the principle beyond the cockpit environment. (2) In the previous studies the i/o modalities of only one task in a dual task pair were varied. The modalities of the concurrent tracking task were always V/M. Hence, any manipulation of i/o modalities inevitably confounded compatibility with resource competition. In the present series of experiments i/o modalities of <u>both</u> tasks are manipulated, thereby allowing us to compare dual task conditions with the same degree of resource competition, but different compatibility.

It is important to be able to examine compatibility effects under dual task conditions. This is because differences in performance between i/o modalities in single task conditions may reflect some component related to the timing of the interfaces involved that is unrelated to the efficiency of human processing. For example, the timing of speech recognition devices is sometimes based upon the latency at which an utterance is categorized by the device. This clearly overestimates the central processing time of the speech response relative to a manuall keypress response by a degree equal to the length of the utterance and the latency of the recognition algorithm.

There are also differences in timing between auditory and visual displays. All visual information becomes available simultaneously and so there is no ambiguity concerning when timing of response latency should start. However, a speech signal inherently becomes available sequentially. If timing begins at the onset of the first sound, then this will probably provide an overestimate of the time actually required to process the information, since processing may begin later. On the other hand, if timing begins at the offset of the sound, human processing time will be underestimated, since partial information is available earlier. The time-course of availability of this partial information is, however, determined by the number of alternative speech stimuli, and their discriminability from each other. Given therefore the potential ambiguities of single task measures of processing latency, we assume therefore that an appropriate estimate of processing efficiency is the interference caused by concurrent activities. This measure, the increase in latency from single to dual task configurations will represent a measure unconfounded by timing artifacts, since these will have equal effects on both single and dual task latency.

In the present series of experiments we have generated two tasks that impose load respectively on spatial and verbal working memory. The <u>threat evaluation task</u> is one in which the subject makes a judgment of the relative velocity vector of an intruding aircraft, and the likelihood that this aircraft will be able to intercept his own. This threat likelihood is then assigned to one of three ordered categories. It is interfaced with either a visual or auditory spatial display, and a vocal or manuall entry of the threat level. The task is assumed to be spatial. The <u>fault diagnosis</u> task is one in which the subject conducts a dialogue, interrogating the computer about the status of a series of systems, each system having a set of components or parts. Both systems and components are labelled by digits. The subject assesses the status of each system in turn. If a given system is abnormal, he must then assess the status of the components within the system. These must be stored in working memory and reported after a system is exhaustively checked. In addition, the subject must keep track of his level in the hierarchy (system level or component level). Thus the task is verbal. In different conditions it is interfaced by verbal auditory and speech display, and either manuall or vocal response.

Our overall design potentially combines the four different i/o combinations for each task, factorially into 16 different dual task combinations. As shown in Figure 2, the i/o modality conditions are arranged in order of decreasing S-C-R compatibility for the fault task (from left to right), and for the threat task (from top to bottom). Compatible S-C and C-R assignments for a given task are labelled by large print, incompatible assignments by small print. In fact, the shaded conditions of Figure 2 were not conducted in the present experiments. These were the four conditions in which both tasks were responded to vocally. Such a condition was not possible with the hardware at our disposal. Furthermore, since the mouth is clearly unable to make two utterances simultaneously, the dual vocal condition is one that would prohibit time-sharing as a result of <u>structural</u> constraints (Wickens, 1983). We desired to investigate conditions in which the only limits to time-sharing were imposed by processing

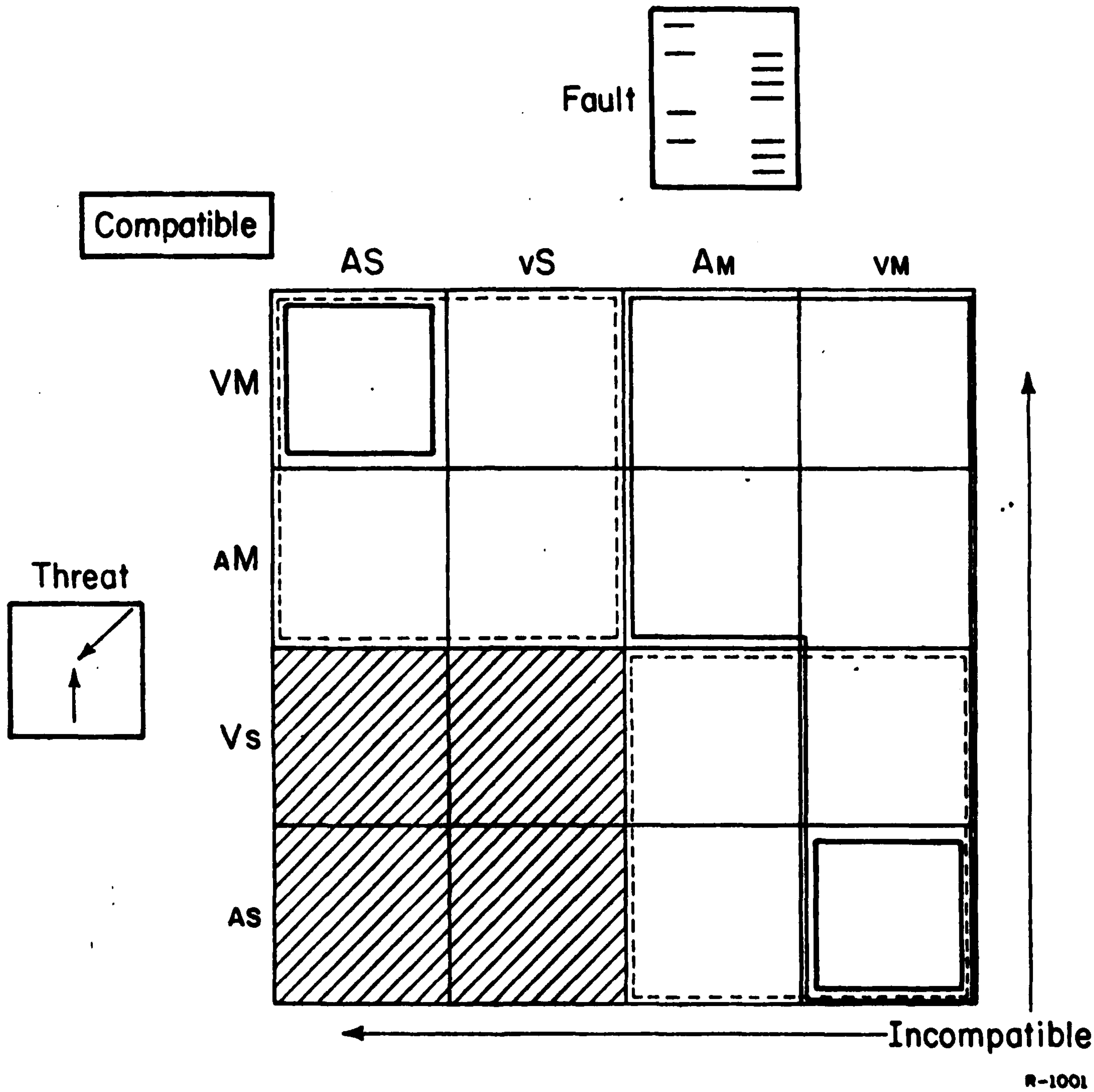

Figure 2: The Experiment Design. Solid line surrounds the conditions investigated in Experiment 1. Dashed line surrounds those in Experiment 2. The heavy squares in the upper left and lower right contrast the two conditions of extreme high and low compatibility.

limitations.

The remaining 12 dual task conditions, to the top and right of Figure 2, were addressed in two separate experiments. Experiment 1 examined performance in the cells surrounded by the heavy outline--those conditions employing a manuall response for the fault task. Experiment 2, employing a different group of subjects examined the cells surrounded by the dashed line. Note that there are two conditions repeated between the two experiments (fault-VM threat-vs, and fault-VM, threat-AS). This allows some estimate of the reliability of our effects. Our major objective then was to assess the manner in which S-C-R compatibility of each of the two tasks, and resource competition between them, combine to produce overall dual task time-sharing efficiency.

Method

Subjects. Twenty right-handed undergraduates at the University of Illinois participated in Experiments 1 and 2. Ten subjects participated in each experiment. All were paid a rate of $3.35 for their participation. Six of the subjects were male in Experiment 1, eight were male in Experiment 2.

Apparatus. Both tasks were implemented on a PDP-11/40 computer. The computer was interfaced to a video display via a HP-3600 Graphics display interface, and received manuall inputs for the subjects via two keyboard devices. Voice interaction with the system was achieved in Experiment 1 with a Centegram Corporation Mike 2 voice recognition and synthesis system. In Experiment 2, an Interstate Electronics voice recognition system was used to recognize subjects' vocal responses.

Threat evaluation task. In the visual version of this task, the subject viewed a series of visual displays such as the three shown in Figure 3. He was to imagine himself flying in the center aircraft in an upward direction. The task was to judge the likelihood that the probe stimulus, the adjacent aircraft in Figure 3, would be at an aspect where it could intercept, or come on a collision course with the subjects' own craft. This "threat likelihood" was then assigned to one of three categories. The stimulus at the top of Figure 3 is of a low threat category since it is behind the subject and opening. The second stimulus is in a medium threat category, while the bottom is in a high category. Thirty-two possible stimuli were defined by the four possible locations of a stimulus and the eight possible compass directions from this location. Of these, eight were deleted because of the absence of an auditory analog. Ten were assigned to the high threat category, six to the medium, and eight to the low category.

On each trial, the threat stimulus was presented by a sequence of two events. First, a light appeared at the location of the plane. Then 500 msec later the light changed to the directional symbol shown in Figure 3. Thus, position and relative velocity information became available sequentially. The reason for this format of information presentation was to make the task compatible with the auditory version described below.

Stimuli were presented at a force-paced rate with an interstimulus interval that varied randomly between 3 and 6 seconds.

The auditory version of the threat task was defined in terms of an auditory spatial "map" that presented the horizontal and vertical

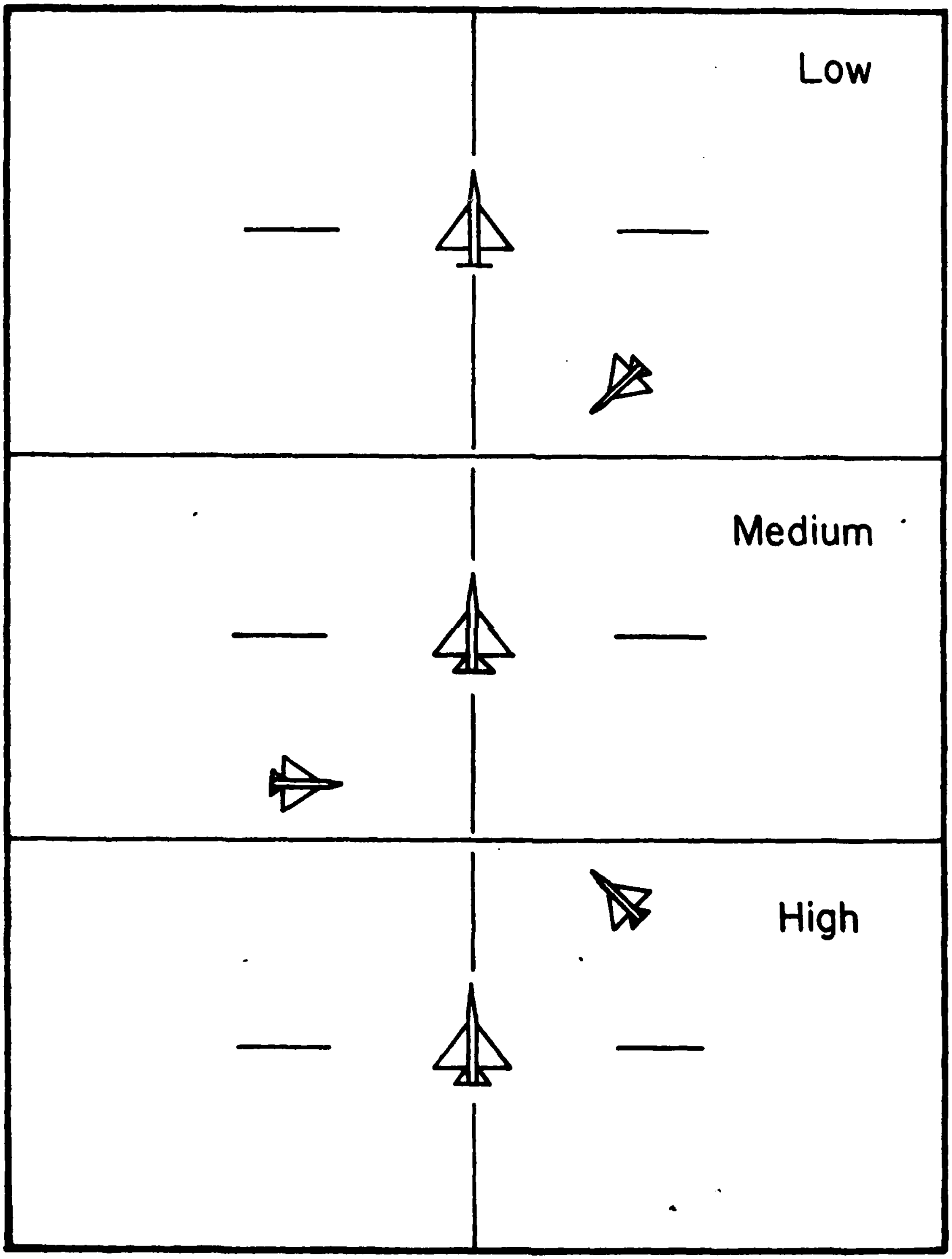

Figure 3: Threat task display showing examples of low, medium, and high threat stimulus categories.

dimensions of Figure 3 in terms of the apparent spatial localization and pitch of a tone, respectively. Three locations were generated by playing tones to the left ear, right ear, and both ears simultaneously through stereo headphones. Four pitches were employed. Thus, auditory information analogous to the low threat situation depicted at the top of Figure 3 would be presented in terms of a low pitched tone to the right ear, followed by a lower tone played to the left ear.

Fault task. This self-paced task required subjects to diagnose faulty systems and components by preceding through a simulated checklist. The structure of the task is shown in Figure 4. The subject would begin by checking each system using the commands "system check 1," "system check 2", etc. After each interrogation, the subject received feedback from the computer; either "yes" or "no." If informed by a "no" that a given system was not functioning correctly, the subject was then required to interogate the computer about the components of that system. This was accomplished by saying: "part check 1, 2, ...", and proceeding through the components of a system with the same dialogue as was done at the system level. After reaching the last part within a system, the subject had to report the failed parts. He then requested to move back to the system level of the hierarchy, and continued the system interrogation until the last of the eight systems was encountered. At this time a final report of all failed systems was given. The computer's report to the subject of system and component states was given either auditory or visually. In Experiment 1 the subjects' interrogation of the computer was entirely accomplished via a manual keyboard which consisted of the eight system/component

FAULT TASK

SYSTEM		COMPONENT		
"1"	YES			
"2"	YES			
"3"	NO			
		"1"	YES	
		"2"	NO	
		"3"	NO	
		"4"	YES	-"REPORT 2,3"-
"4"	YES			
"5"	NO			
		"1"	YES	
		"2"	YES	
		"3"	NO	
"7"	YES			

"FINAL REPORT 3,5"

Figure 4: Typical examples of the dialogue in the fault task. Utterances in quotes are those given by the subject. Yes, no responses are given by the system.

keys, along with two mode keys that were pressed whenever the subject wished to change between the system and component modes, a "report" key, depressed when the subject wished to report the failed system or components, and a "check" which was used to interrogate the computer about system or component status. In Experiment 2, in addition to the keyboard entry, a voice entry was used in which the subjects interrogated using natural voice commands (e.g., "check part 1"). In the voice entry condition of Experiment 2, feedback of the form "repeat" was provided whenever the voice recognition system failed to identify the subjects' vocal utterance as a part of its vocabulary.

Procedure. Prior to each trial, subjects were informed as to which task(s) and what input/output modalities would be employed. On dual task trials they were asked to give both tasks equal priorities and to try to maintain a level as close to their single task performance as possible. For the fault task and the dual task combinations, trial length varied, since a trial terminated when a subject completed the fault task interrogation. Trials lasted around 1 to 1 1/2 minutes. The duration of the threat trial when performed by itself was consistent at 20 probes.

Design - Experiment 1 . The cells that are enclosed by the heavy solid line shown in Figure 2 constitute the six dual task conditions run in Experiment 1. In addition, the corresponding six single task conditions were also run. These involved all four i/o modality combinations of the threat task, and the two input modalities of the fault task assigned to the manuall response (A/M and V/M). Subjects participated for a total of five sessions, each session lasting approximately 1 hour. During sessions 1-3 subjects received extensive practice on all combinations of the tasks. The experimental data used in the analysis below was collected on sessions 4 and 5. Each of these sessions were identical in format consisting of 24 trials. Each session consisted of two blocks of the 12 trial types. Each block was given in a different random order of trial types.

Results: Experiment 1

Single task data. Two primary measures of performance for the threat task were extracted: response latency and accuracy, the percentage of errors made in classifying the target threat category. These are shown in the top and bottom of Figure 5, respectively. The abscissa depicts the four I/O modality combinations in order of decreasing S-C-R compatibility for the spatial threat task. Each of the dependent variables were submitted to a 2 (input) x 2 (output) repeated measures analysis of variance. As suggested by the data in Figure 5, performance latency as both the input ($F_{1,9} = 76.22$, $p < .001$) and the output ($F_{1,9} = 407.95$, $p < .001$) were changed to the incompatible auditory and speech modalities, respectively. Performance accuracy was uninfluenced by output modality ($p > .6$), but was strongly degraded by the auditory input ($F = 19.41$, $p < .002$).

Three measures of performance on the fault task were assessed. A latency measure, the time per operation or TPO was derived by dividing the total trial length by the number of operations (keypresses) performed. Two accuracy measures were computed using the signal detection sensitivty measure, A' (Craig, 1979). These assessed the accuracy of memory for failed systems and for failed parts. The signal

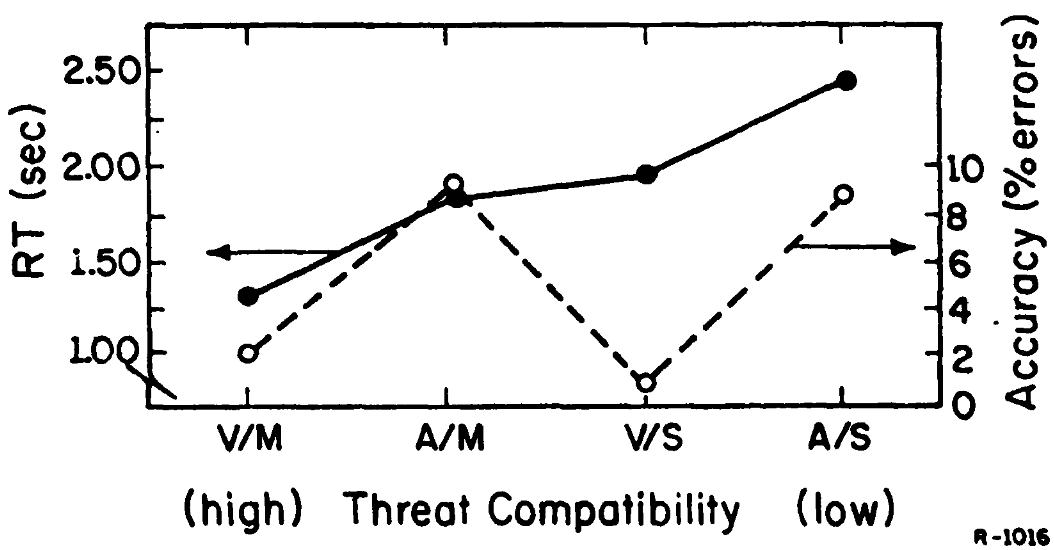

Figure 5: Single task threat performance (Experiment 1).

detection measure was employed to account for the two kinds of errors of recall subjects could make. Errors of omission (neglecting to report a failed component), which determined the hit rate, and errors of commission (reporting an element as failed that was, in fact, normal) which determined the false alarm rate. Table 1 shows these three dependent variables as a function of the two single task conditions. Performance with visual display was faster and less accurate, although for all three measures the differences between displays were not significant.

Dual task performance. Because the design that we employed was not an orthogonal one, the dual task data were not analyzed using a single Omnibus ANOVA. Instead, it was our intention to ask specific questions of the data using a series of three ANOVAs on overlapping cells of the solid outlined area in Figure 2. For appreciation of the meaning of these ANOVAs, this area is reproduced in Figure 6, with each cell now labelled in terms of the characteristics of the task configurations that are combined within the cell. The large digit at the top of the cell reflects the number of modalities for which there is resource competition: e.g., zero for the T(A/S)-F(V/M) conditions, and two for the T(V/M)-F(V/M) condition. Higher numbers thus predict greater interference and hence poorer performance according to resource theory. Within the brackets at the bottom, the two digits indicated the number of S-C-R incompatible modalities for the threat task (digit on the lower left) and the fault task (digit on the upper right). Thus in both cases higher digits predict poorer performance.

Table 1

Single Task Fault Data

(Experiment 1: Manual Response)

Fault Display		TPO (sec)	A' (system)	A' (part)
	Visual	1.80	.79	.93
	Auditory	1.89	.84	.95

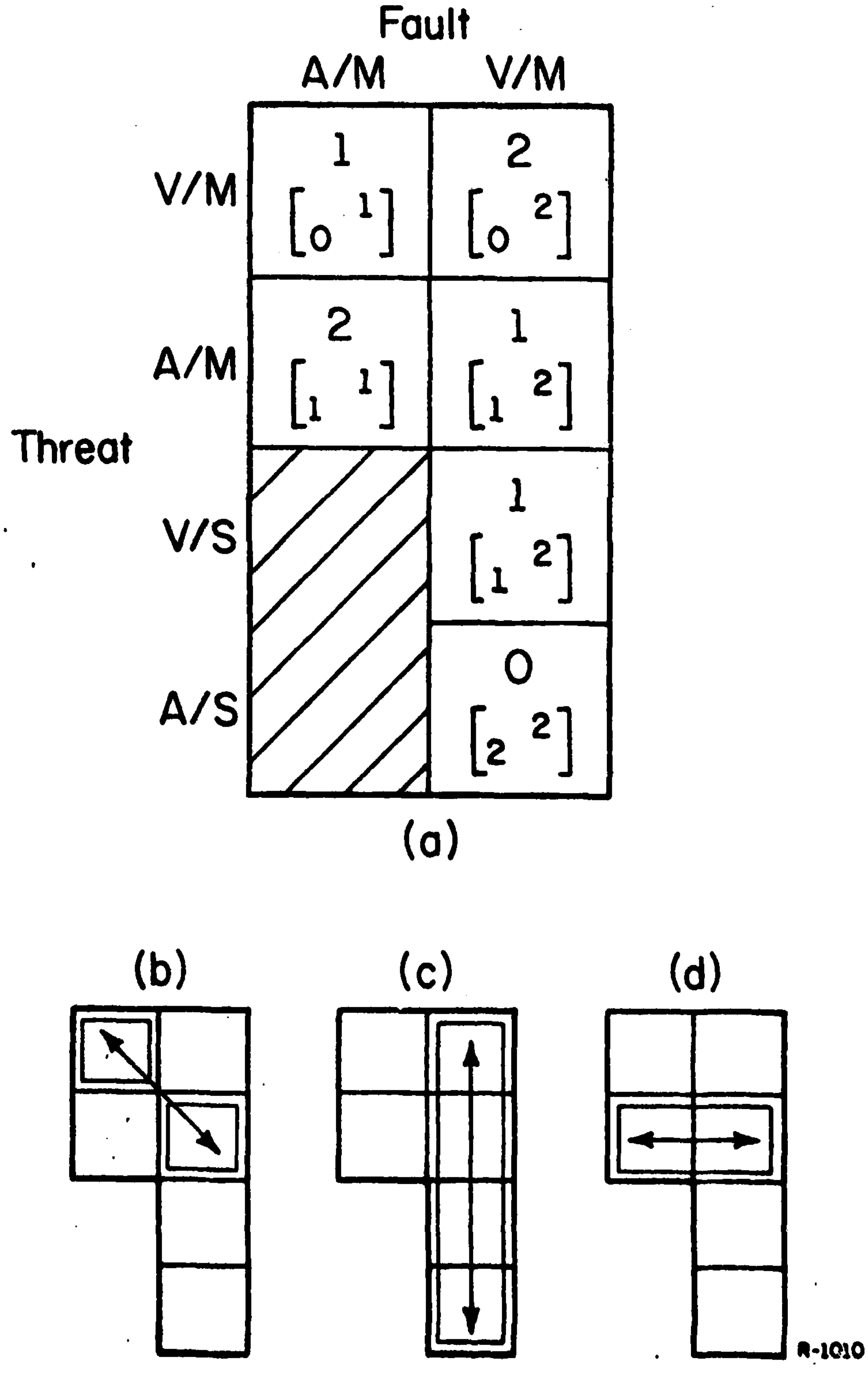

Figure 6: Shows the 3 ANOVA contrasts made on the data of Experiment 1. The large digit in each cell indicates amount of competition for i/o resources. The small digits within brackets indicate the number of S-C-R incompatible mappings.

The raw dual task data for all dependent variables are presented in Table 2 and organized in the same framework as Figure 6. However, to aid in interpreting the results in terms of task interference, we shall present the data in graphical form as decrements in performance from single to dual task conditions. As noted in the introduction, this format has the advantage of removing any artifacts from the data that might be related to timing constraints on the speech recognition and syntheses devices, and provides an estimate of the loss in human information processing speed that results in a given dual task situation.

Finally, the statistical analyses of these data is accomplished not on the decrement scores themselves, as we have done in previous studies, but by using an analysis of covariance procedure in which the raw dual task data are analyzed with the single task scores as covariates. The analysis thus reflects variances between dual task conditions not accounted for by variance between single task procedures, but does so in a manner that is not sensitive to the regression-to-the-mean artifacts which may influence any decrement analysis (Ackerman & Wickens, 1982).

The following three dual task analyses then describe the contrast between the cells highlighted in the bottom of Figure 6. We consider these particular contrasts important either because they allow us to examine the influence of one variable (competition or compatibility) uninfluenced by the other, or because they allow us to examine both variables in an orderly combination with each other.

Table 2

Dual Task Data

Threat Task

Latency (sec)
Accuracy (% corr)

Threat i/o Modality	Fault i Modality: A/M	Fault i Modality: V/M
V/M	1.81 96.2	1.85 95.0
A/M	2.20 85.6	2.34 86.8
V/S		2.31 94.8
A/S		2.70 89.8

Fault Task

TPO (sec)
A' System
A' Component

Threat i/o Modality	Fault i Modality: A/M	Fault i Modality: V/M
V/M	2.36 .839 .947	2.29 .863 .957
A/M	2.52 .724 .915	2.55 .786 .930
V/S		2.26 .856 .947
A/S		2.49 .787 .942

Comparison 1: Effect of S-C Compatibility

The two conditions contrasted in Figure 6b are both identical in terms of resource competition (competition for manuall response, separate inputs), but differ with regard to which input is assigned to which task. When the threat task is V/M and fault is A/M, both are maximally S-C compatible. When inputs are switched, both are incompatible. The data for these two conditions are shown in Figure 7, in which the decrements of both tasks on both dependent variables from their single task controls are shown. Only the A' measure for part accuracy is shown. In general, the results were quite consistent in indicating superior performance for both tasks in the compatible condition. For the threat task at the top of the figure, this superiority was manifest primarily in the accuracy measure. There was a greater decrement in threat accuracy from the single task conditions in the incompatible than the compatible configuration ($F_{1,8} = 3.63$; $p < .093$). The time decrement, while slightly larger in the incompatible condition, was not reliably different ($p > .10$). For the fault task shown below, the compatibility effect was only significant for the time-measure TPO ($F_{1,8} = 10.70$, $p < .02$). The differences for the two accuracy measures (A' system and A' component) were not statistically reliable (both p's > .10).

Comparison 2: S-C-R Threat Compatibility vs. Resource Overlap

The four cells that are highlighted in Figure 6c are designed to examine the opposing effects of S-C-R compatibility and resource overlap, an effect explicitly examined by Sandry and Wickens (1982).

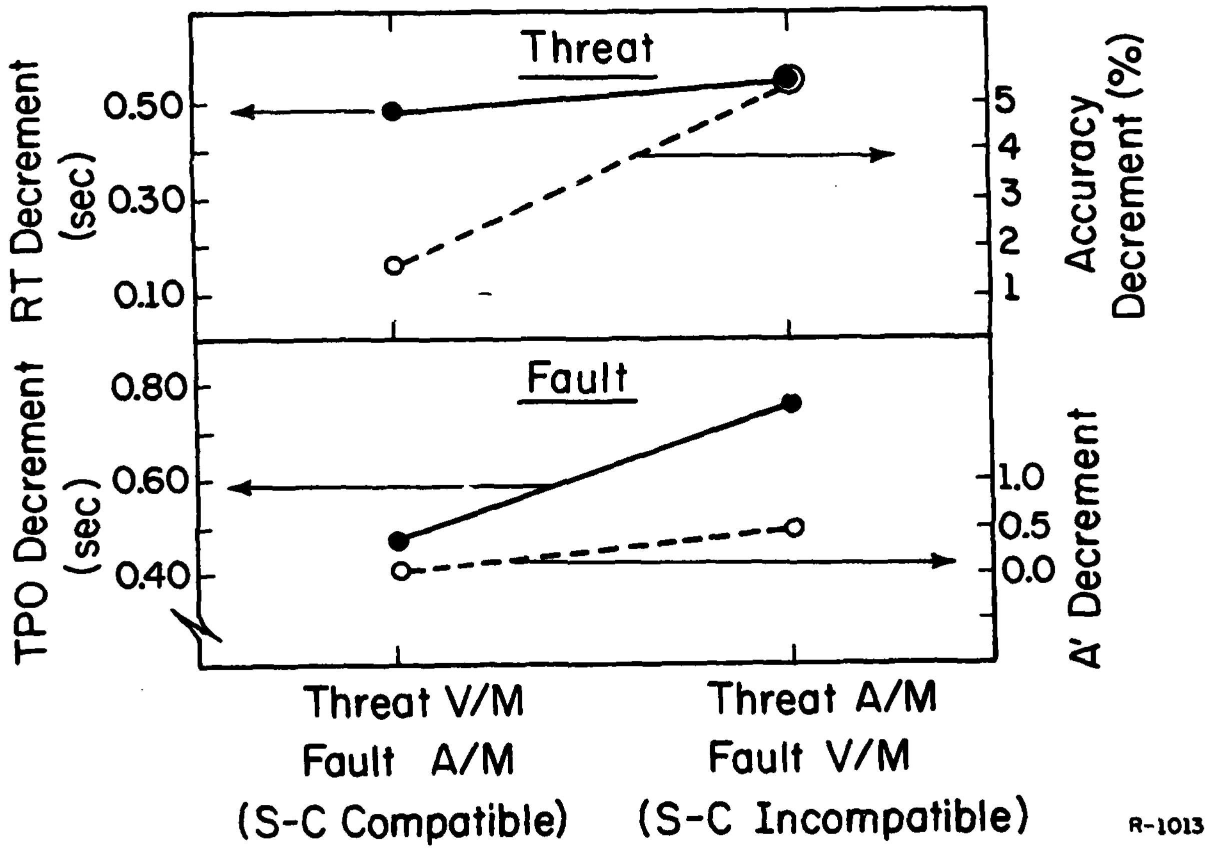

Figure 7: Data in contrast (b) of Figure 6.

They showed that if the input/output modalities of a spatial task were varied, when it was time-shared with a visual-manuall task such as tracking, then the modalities that were most S-C-R compatible for the spatial task (V/M) would also be those imposing the greatest resource competition. Hence the compatibility effects across i/o modalities observed in single task conditions should be attenuated in dual task conditions. Or, viewed from a different perspective, the expected effect of greater interference with more overlap of i/o modalities should be attenuated.

By comparing the cells shown in Figure 6c, we have an opportunity to replicate the findings of Sandry and Wickens with the different tasks used here. The relevant data for this comparison are shown in Figure 8. Note for comparison that the abscissa is the same as in Figure 5. It is apparent from the figure that in accordance with the argument presented above, the expected effect of decreasing time-sharing decrement with decreasing I/O overlap (moving from left to right) is not pronounced in these data. Threat performance, as assessed by both latency and accuracy, appears to be generally unaffected by I/O inputs (F values for both input and output modalities for both latency and accuracy generated p values > .10). (There does appear to be a reduced decrement with the manuall response, and this was in fact, significant ($F_{1,9} = 7.67$, $p < .03$) when decrement scores were analyzed rather than the analysis of covariance technique.)

When the fault data are examined in the bottom of Figure 8, the effect of output modality again failed to be significant, while a significant effect of input modality on TPO was obtained in the

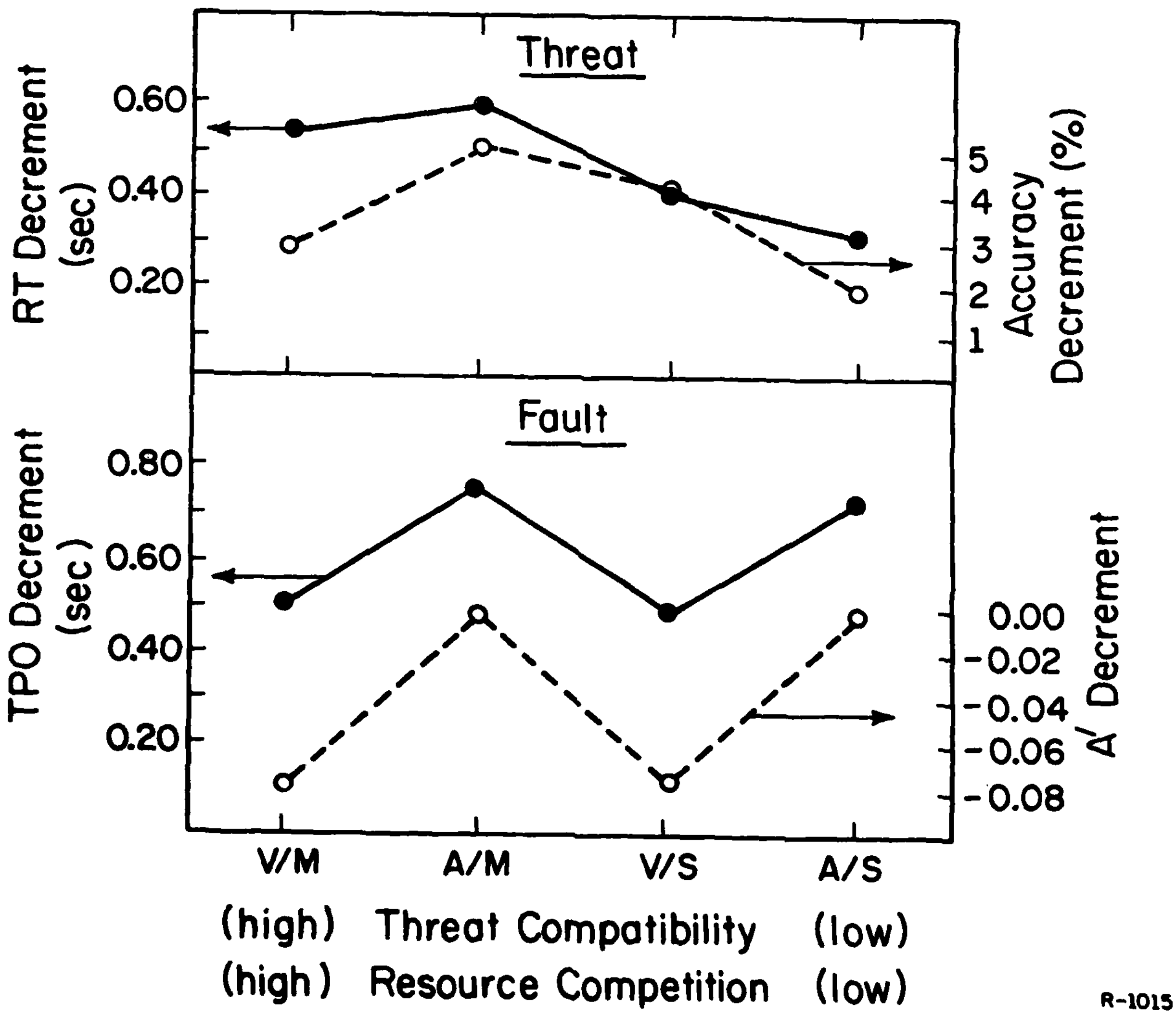

Figure 8: Data in contrast (c) of Figure 6.

opposite direction predicted from resource competition ($F_{1,9} = 24.07$; $p < .01$; the effect on system accuracy, while in the same direction, was not reliable). That is, the time-sharing decrement was actually smaller in the condition of shared visual inputs. This result suggests that the compatibility advantage of the visual threat display over its auditory counterpart, was sufficiently great so as to more than compensate for any task competition within the visual system, in the two visual conditions [threat(V/M) and threat(V/S)].

Comparison 3: S-C Fault Compatibility vs. Resource Overlap

The two cells highlighted in Figure 6d compare the condition in which the fault task is S-C compatible (auditory display) but competes with the threat task for auditory input, with that in which the fault task is incompatible, but utilizes a separate input channel. As in Comparison 2, we anticipate that the expected influence of resource competition will be effectively reduced or even cancelled by the advantages of compatibility. Here again, the dependent variables shown in Figure 9 support this prediction. For both tasks, the effect of changing the fault display to the incompatible visual modality is to produce a small, non-significant increase in accuracy (a reduced decrement), and a small, also insignificant increase in latency.

In summarizing the results of Experiment 1, we note the following general trends:

1) The single task S-C-R compatibility effects were generally upheld for both tasks, although C-R compatibility was not manipulated for the fault task.

2) These effects were manifest and sometimes amplified under dual

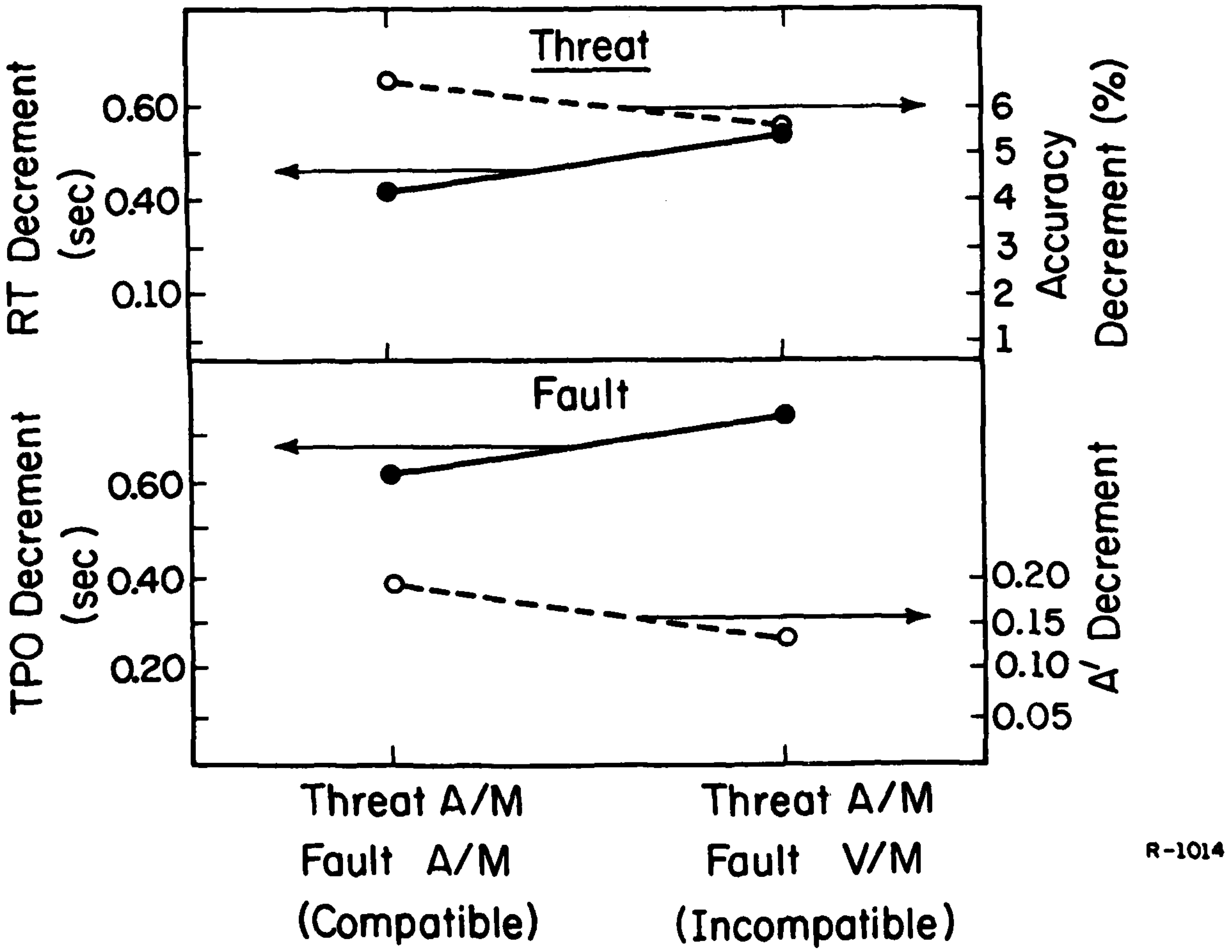

Figure 9: Data in contrast (d) of Figure 6.

task conditions. The amplification was reflected when a decrement was larger in an incompatible than a compatible assignment. The amplification due to incompatibility was sufficient in some cases to balance and overrule the advantages of separate resources between tasks. This was particularly true when the incompatible auditory-spatial display was employed for the threat evaluation task. We assume that the added demand on processing resources imposed by this incompatible display was large and sufficient to neutralize any advantage to the use of separate resources of encoding as demonstrated in the second contrast (Figure 6c). The more general implications of these results will be considered after a discussion of the results of Experiment 2.

Experiment 2: Method

Ten new subjects were recruited to participate in Experiment 2 which investigated the eight dual task conditions surrounded by the dashed line of Figure 2. The procedures in Experiment 2 were very similar to those followed in Experiment 1, with the addition of a final session in which priorities between the two tasks were manipulated (Navon & Gopher, 1979).

The eight single and eight dual task configurations surrounded by the dashed line in Figure 2 were first practiced across three one hour sessions. Day 1 provided practice on the eight single task conditions. Particular emphasis was given to practicing the auditory displayed version of the threat task, as this was found in Experiment 1 to be considerably more difficult than the others. Day 2 emphasized dual task conditions. Days 3-6 each contained one complete experimental block of the eight single and eight dual task conditions presented in random order. The data collected on Day 3 were considered practice. The data from sessions 4-6 were the experimental data upon which the following analysis is based. Finally, on Day 7, 31 trials were presented in which we assessed the ability of subjects to adjust performance or allocate attention between the two tasks according to priorities. This was only done for six of the dual task conditions: The four cells in the lower right corner of Figure 2, and the two conditions with A/S modalities for the fault. For each of these six configurations were replicated once with emphasis placed on fault and once with emphasis placed on threat, for a total of 24 dual task trials. One condition of each of the seven single task trials was also presented.

Results: Experiment 2

Single Task Performance

Table 3 presents the single task latency and accuracy data from the eight single task conditions of Experiment 2. At the top the latency of response to the threat task shows the expected compatibility effects. That is, reaction times were longer when the input was auditory ($F = 33.3$, $p < .001$), and when the response used speech ($F = 96.5$, $p < .001$). These effects replicate very closely those portrayed in Figure 5 of Experiment 1. Of course, as pointed out in discussing Experiment 1, the second of these effects cannot necessarily be attributed to human processing latency as some component reflects the difference in the computer timing latency associated with the voice recognition unit. Single task threat accuracy, like response speed,

Table 3

Single Task Latency & Accuracy Data

	Threat Task			
	V/M	A/M	V/S	A/S
RT (sec)	1.22	1.61	1.78	2.14
Accuracy	96.5	92.8	98.7	96.5
	Fault Task			
TPO	1.96	1.80	3.42	3.48
A' part	.989	.989	.928	.980
A' system	.975	.968	.973	.990

was also degraded by the auditory condition ($F = 5.7$, $p < .04$). However, the response modality effect on accuracy was opposite that predicted by compatibility and found with latency. Subjects were more accurate with the speech than with the manuall response ($F = 11.3$, $p < .01$). Therefore, while single task input compatibility effects of the threat task are robust and consistent across both latency and accuracy, the output compatibility effects are less consistent in Experiment 2: A shorter It should be recalled that in Experiment 1 threat output modality had no effect on accuracy.

For the fault task, the time/operation (TPO) was slowed considerably by the speech response ($F = 144.3$, $p < .001$). Once again, this effect cannot necessarily be attributed to human processing differences. This is because, given the self-paced nature of the fault task, the greater latency of the speech recognition system retards the subject's overall progress in proceeding through the hierarchy. The main effect of input compatibility on TPO was not statistically reliable; however, input modality did affect latency indirectly through a 2-way interaction with output modality ($F = 6.2$, $p < .04$). When the output was speech (compatible), then input modality had little effect on TPO (a slight speeding with the incompatible visual format). However, when the output was manual (incompatible), performance with the incompatible visual input was considerably degraded. This effect is probably attributable less to compatibilty effects than it is to the fact that subjects needed to rely upon some visual feedback for keyboard input in the manual response condition. When input was also visual, some competition for the visual channel consequently arose.

The accuracy measures of the fault task showed no main effects, and only one interaction which was not readily interpretable.

Dual Task Performance: Equal Allocation

The eight dual task conditions investigated in Experiment 2 and shown in the dashed squares of Figure 2 were analyzed in terms of single-dual task decrement scores rather than the analysis of covariance procedure. The design used to analyzed decrements in each of the dependent variables for the two tasks, represented the eight dual task conditions in terms of three two-level factors. (1) Response compatibility contrasted the four cells in the upper left of Figure 2 in which the response modality of both tasks was compatible, with the four in the lower right in which the response was incompatible. (2) Fault input compatibility contrasts the four conditions in which the fault task is auditorily displayed with the four visual conditions. (3) Threat input compatibility in turn contrasts the four conditions with high compatible visual inputs to the threat task with the four low compatible auditory inputs. It will be noted that this particular way of defining the input compatibility factors makes the effect of resource competition somewhat more difficult to interpret. For example, the conditions of high input compatibility on both tasks (hi-hi) and low compatibility on both tasks (low-low) are both those of minimum resource overlap. The conditions of intermediate input compatibility (compatible on one task, not on the other) are the conditions of maximum resource overlap (AA or VV). The effect of resource overlap will be dealt with in a later section.

As in Experiment 1, the most robust effects of task configuration were manifest in the latency data of the two tasks. Hence, these will be the primary focus of our discussion. Figure 10 plots the single minus dual task decrement data for the latency measures of each task, RT for threat at the top. TPO for fault is below. The panels on the left and right represent high and low compatibility response assignments, respectively. The points on the left of each panel are high compatible (auditory) fault displays. The solid lines within each panel are high compatible (visual) threat displays.

The threat RT decrement data shown at the top of Figure 10 present a fairly orderly picture of the influence of compatibility on dual task performance decrements. The decrements were larger when the fault task was displayed incompatibly (visual) ($F = 10.1$, $p < .02$), and when both tasks received an incompatible response assignment ($F = 12.1$, $p < .01$). There is also an apparent effect of threat input compatibility upon the decrement in the threat task itself, the dashed lines lying above the solid. However, this effect was not statistically reliable ($p > .10$).

Analysis of the threat accuracy decrement data not plotted here is consistent with the latency data. The only reliable effect was a greater loss of accuracy in with the less compatible auditory display for the threat task ($F = 27.6$, $p < .05$). The other effects that were reliable with latency failed to influence accuracy. However, accuracy did vary in a manner such that larger accuracy decrements occurred in conditions associated with greater latency decrements. Hence, the results are not artifacts of a speed accuracy tradeoff.

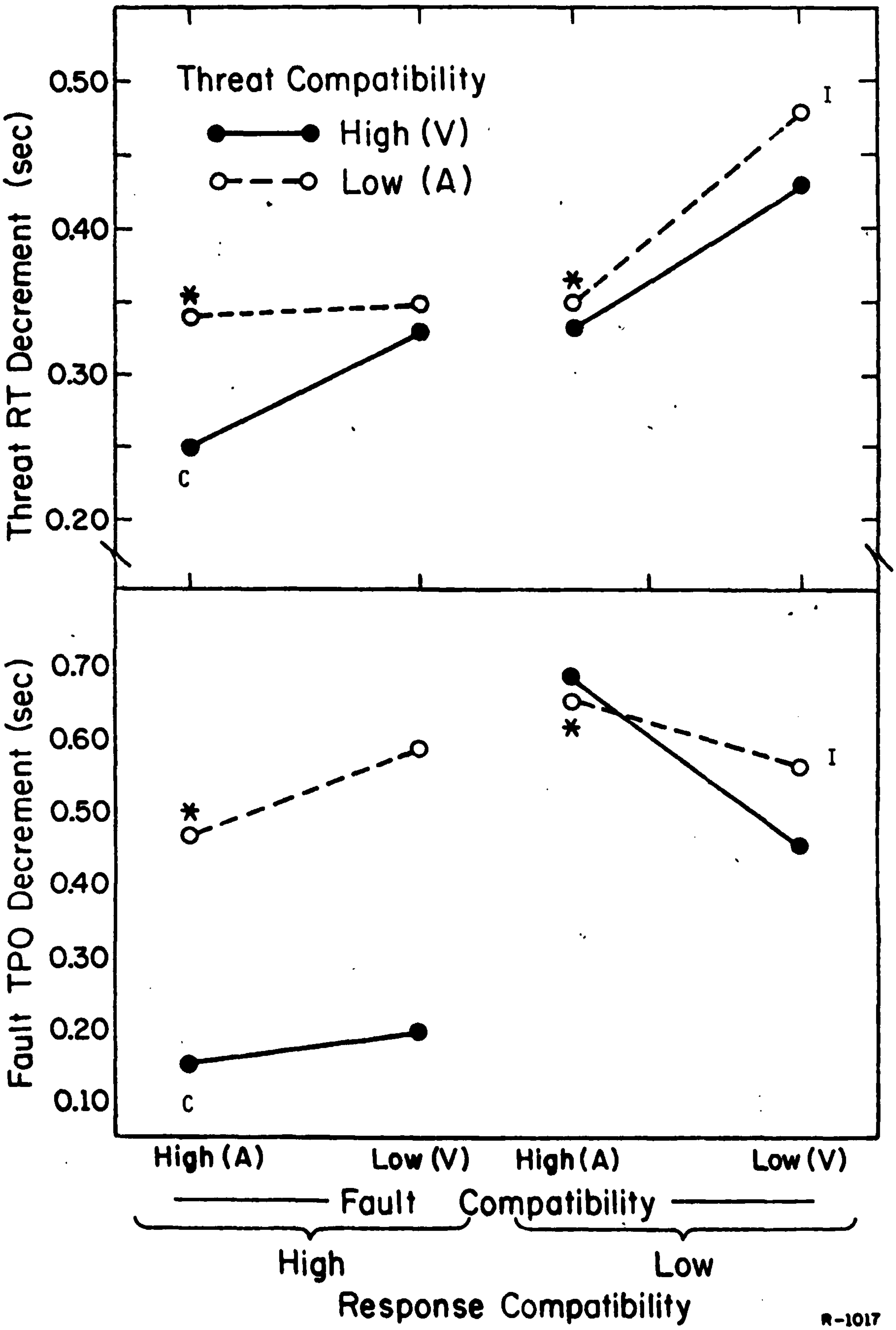

Figure 10: Threat and fault latency data in Experiment 2. The (*) indicates those conditions in which there is auditory stimulation coming from three sources.

Dual task performance decrements in the TPO measure of the fault task formed a somewhat more complex picture, represented in the bottom of Figure 10. Both the main effects of threat input compatibility and response compatibility were reliable and in the predicted direction ($F = 11.6$, $p < .01$ and $F = 9.9$, $p < .01$), respectively). The two effects influenced each other as suggested by the difference between the two lines in the left and in the right panels (F/interaction = 13.3, $p < .01$); displaying the threat task compatibly (visual) only improved time-sharing efficiency when the response configuration of both tasks was also compatible.

While the effect of fault task input compatibility, indicated by the slope of each line in Figure 10, did not influence its own decrement directly, it exerted less direct effects in the form of interactions with the two other independent variables: Decreasing fault compatibility seemed to disrupt performance when response compatibility was high (the left panel, a consistent effect with the threat data above), but to improve performance when response compatibility was low in the right panel ($F = 9.6$, $p < .02$). It is not immediately apparent how to interpret this interaction. One way is to consider the right panel of both the threat and fault decrements collectively, in contrast with the left panel. When this is done it is apparent that some sort of tradeoff is taking place when the fault task is displayed auditorily. There is a gain to dual task threat performance, but this is achieved at the expense of performance on the fault task itself. Yet this only happens when the response assignment is incompatible.

A second interaction is found between input compatbility of the two tasks. At both levels of response compatibility (the left and right panels), the harmful effect of low compatibility of one task is enhanced by low compatibility of the other ($F = 5.57$, $p < .05$). That is, the two lines in each panel diverge from left to right. This effect is quite predictable. Input compatibility effects enhance each other. As with the threat task, the effects reported on the fault time decrement do not appear to be attributable to a speed accuracy tradeoff.

The only reliable main effect or 2-way interaction on either the system or part accuracy measure (A') was an effect of threat task compatibility. This effect indicated greater accuracy with the more compatible visual threat display. The three way interaction was also reliable for the part accuracy measure ($F_{1,9} = 9.7$, $p < .02$). Closer scrutiny suggests that this interaction is attributable in large part to an "auditory overload" effect. That is, there was a particularly great loss in accuracy (attributed to a particularly high false alarm rate) that occurred when both the threat and fault task were displayed auditorily, and the fault task was also responded to vocally. This is the only condition in Experiment 2 in which there were three sources of auditory input: from the two displays and from feedback of the subject's voice. The auditory modality is apparently less equipped for parallel processing than is the visual (Isreal, 1980).

Extreme groups comparison. The preceding analysis has discussed compatibility along three independently varied dimensions. The results were somewhat complex, and in the case of each dimension, manipulations of compatibility were to some degree confounded with the degree of resource competition between tasks. A second analysis of Experiment 2 was designed to provide a comparison of the two conditions that differed most in their degree of compatibility and were otherwise identical in terms of resource overlap: That is [threat(VM) - fault (AS)] (maximally compatible) vs. [threat(AS) - fault (VM)] (minimally compatible). Both of these configurations have in common the characteristic that neither involves any competition for input or output modalities; as such, their comparison provides a "pure" estimate of the magnitude of compatibility effects on time-sharing performance. In Figure 10 these two conditions are indicated by the letters C and I next to the maximally compatible and incompatible points, respectively.

The analysis revealed that the difference across these conditions was consistent and large. When the assignment was made incompatible the threat task time decrement and acccuracy decrement were increased by 280 msec and 7.6%, respectively ($F(1,9) = 6.64$, $p < .03$; $F(1,9) = 17.4$, $p < .01$, respectively). The decrement in the time per operation of the fault task increased by over half a second ($F(1,9) = 11.0$, $p < .01$), and the accuracy of reporting both parts and systems declined as well, by roughly 6% although in neither case were the effects reliable (fault A': $F = 2.65$, part A': $F = 3.07$). Hence, the difference between the extreme compatibility groups was consistent across both measures of latency and accuracy of both tasks.

<u>Resource competition effects</u>. To this point, the influence of resource competition has only been discussed indirectly as a factor that is attenuated by compatible inputs or, alternatively reduces the

effects of compatibility. The purpose of the present reanalysis of the data is to examine the influence of resource competition directly. This was accomplished by using the same data set presented in Figure 10, but redefining the fault input compatibility factor so that conditions of high resource competition (auditory or visual inputs on both tasks) were defined as a different level of the variable from conditions of separate inputs on the two tasks. This reanalysis has the effect of expressing any resource competition effect as a main effect, whereas in the previous analysis it was manifest as an interaction between threat and fault input compatibility, and thus subject to alternative interpretations.

The results of this analysis were consistently negative. Of the five primary dependent variables, the only two that showed a reliable main effect of resource competition were the fault task TPO decrement ($F(1,9) = 5.57$, $p < .05$), and the threat accuracy decrement ($F(1,9) = 27.59$, $p < .01$). Both of these effects were in fact in the <u>opposite</u> direction predicted by resource competition. That is, there were slightly reduced decrements in the conditions where both tasks were presented in the same modality. The effect of resource competition on these variables was modified by the other factors in only one respect, which has been described earlier. That is, an interaction between resource competition and threat task input on the threat RT decrement indicates that performance actually benefits considerably by dual visual inputs, but suffers somewhat by dual auditory inputs: Auditory time-sharing is more difficult than visual.

Dual Task Performance: Bias Analysis

Generally the bias instructions had little effect on task performance. For both tasks, performance speed increased if the task was emphasized. However, this effect was only significant for the threat RT decrement ($F_{1,6} = 6.57$, $p < .05$). In neither task was accuracy influenced by the request to emphasize one or the other. In one sense these absences of effects are predictable. The two tasks, threat and fault were designed to place heavy loads on spatial and verbal processes, respectively. According to the multiple resources model (Wickens, 1983), these should demand separate codes of information processing. If separate central processing resources are used by the two, then the operator should not be able to "tradeoff" these resources even if requested to do so by instructions. Indeed this inability is precisely what was indicated by the data.

A second negative result of the bias analysis was also interesting from the point of view of resource theory. This was the total absence of any interaction of bias with input factors. Had such an interaction been obtained, it would have suggested that input modalities behave like resources: When two tasks demand a common modality they can be traded off, better than when they do not. The fact that a differential tradeoff was not observed suggests instead that modalities behave more like dedicated processing structures.

Combined Analysis: Experiments 1 and 2

Reliability. The experimental design, represented in Figure 2, shows that two conditions were replicated in both experiments. These were the conditions when the visual manual fault task was paired with the VS and AS versions of the threat task. We were interested initially in determining the reliability of our experimental manipulations across experiments. How similar were the increases of performance between the two, and how similar were the effects of threat input compatibility?

To investigate reliability we submitted the data from these cells to a 2 x 2 mixed factor ANOVA with "Experiment" (1 vs. 2) as the between-subject factor and threat input varied within subjects. The results confirmed that our manipulations were reliable. Of the five dependent variables (threat latency and accuracy decrements; fault TPO decrement, system A' and part A'), only one variable, system A' differed reliably between experiments. Subjects were more accurate recalling system failures in Experiment 2 than in Experiment 1 ($F_{1,18}$ = 12.95, $p < .01$). The reason for this difference is not apparent. More importantly, the ANOVA failed to produce any reliable interactions between threat input and experiment. This absence of effect was reassuring. It suggested that all effects of this one variable that we found in one experiment were replicated in the second.

Fault compatibility. The fact that the data from the two experiments were apparently comparable, as revealed by the reliability check, allowed us to combine certain conditions from each experiment in a between-groups analysis, and test yet another characteristic of the compatibility-resource hypothesis. This analysis incorporated the top half of Figure 2. That is, all of those conditions in which the threat task was responded to manually. These conditions are important because they define the circumstances under which changing S-C-R compatibility will have the greatest impact on dual task performance (Wickens, Sandry, & Vidulich, 1983). Moving from left to right across the top of the figure will create conditions of progressively lower fault compatibility and, for the top row (visual threat) progressively greater resource competition. For the second row (auditory threat) resource competition is also greater for the two cells on the right (manual response competition) than for the two on the left, although within each of these pairs, the effects of compatibility and input competition counteract each other.

Five 3-way, threat input x fault input x fault response mixed analyses of variance were performed on the data, examining each of the five standard variables. The results of these ANOVA's were quite consistent in demonstrating the pronounced and expected effects of threat input/output manipulations on dual task performance. Figure 11 plots the threat task RT decrement as a function of decreasing S-C-R compatibility and increasing resource overlap. The plot is inverted, so that good performance, small decrements, are to the top of the figure. Performance for each of the two threat inputs is indicated by the separate graph.

It is apparent from Figure 11 that the expected monotonic decrease in performance with decreasing compatibility is obtained. This is particularly evident with the visual threat display, the dashed line, for which incompatibility and resource overlap are perfectly correlated. Thus for the threat RT decrement reliable main effects of fault input ($F_{1,18} = 5.99$, $p < .03$) and output ($F_{1,18} = 3.70$, $p < .07$)

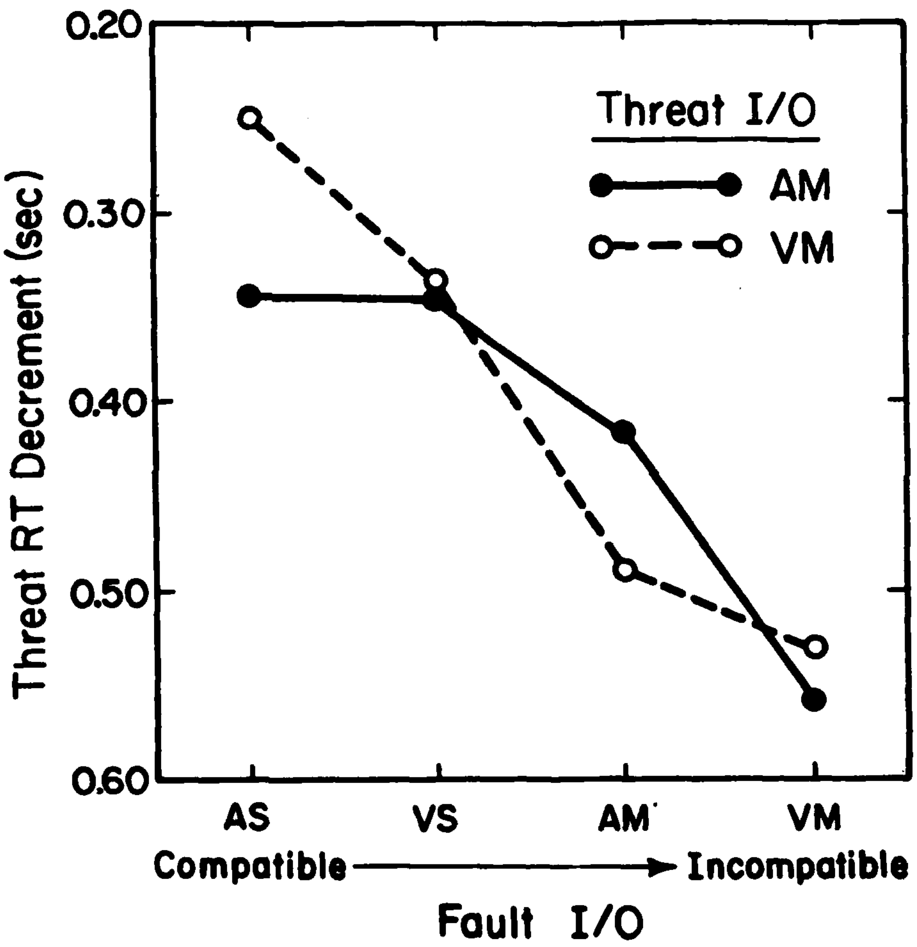

Figure 11: Results of combined analyses of both experiments: Threat RT decrement as a function of S-C-R compatibility of the fault task, and S-C compatibility for threat. The decrement is plotted on an inverted scale, so that better performance is higher on the graph.

were observed.

There was also a reliable three-way interaction between the variables ($F1,18 = 4.85$, $p < .05$). This interaction can seemingly be most readily accounted for by the lower than predicted level of performance with the A/S fault paired with the auditory threat display (i.e., the solid point at the far left of Figure 11). If this point were raised, the three-way interaction would disappear. A logical inference is that this point was particularly low as a result of the "auditory overload" effect described above. That is, the conflict between the three sources of auditory information: Auditory input on both tasks and vocal feedback from the speech reponse to the fault task.

The threat RT decrement was the only one presented in the figure because only this variable showed higher level interactions. However, the other four variables all exhibited consistent and reliable main effects in the direction predicted by compatibility. These effects and the values of the cell means are shown in Table 4. As can be seen, every reliable effect in the table indicates poorer performance (or larger decrement) with the input/output assignment that was predicted by the model to be of lower S-C-R compatibility. This condition is underlined a the top of each column.

Discussion

The results of Experiments 1 and 2 together are numerous, and considered one by one they portray a fairly complex picture. However, considered collectively, the results are consistent and allow a general summary statement to be made: In the tasks considered here, S-C-R

Table 4

Reliable Effects of Between-Experiment Analysis
(Degrees of Freedom = 1,18)

	Threat Input		Fault Input		Fault Response	
THREAT	AUD	VIS	AUD	VIS	Speech	Manual
RT Decrement (sec)			3.73	4.39	3.17	4.96
			$F = 5.9$; $p < .03$		$F = 3.70$; $p < .07$	
ACC Decrement (%)	5.1	.025			1.0	4.15
	$F = 15.8$; $p < .001$				$F = 3.57$; $p < .08$	
FAULT						
TPO Decrement	6.11	3.30	4.33	5.08	3.56	5.85
	$F = 45.28$; $p < .001$		$F = 3.3$; $p < .09$		$F = 5.97$; $p < .03$	
A' System	.85	.91			.957	.803
	$F = 6.09$; $p < .03$				$F = 20.92$; $p < .01$	
A' Part	.923	.953				
	$F = 8.75$; $p < .01$					

compatibility is a more dominating force than is resource competition. This statement can be justified by three aspects of the data: The effects of compatibility unconfounded with resource competition, the effects of resource competition unconfounded with compatibility, and the effects of both variables pitted against each other: These three will be considered in inverse order.

First, in the contrast of Experiment 1 (Figure 6d and Figure 9) when competition was pitted against compatibility, the two forces generally neutralized each other. However, in at least one case, performance decrements were smaller in a display configuration in which both tasks were visual (competition), but at least one was compatible, than in the condition in which neither task was compatible but separate inputs were used. Second, in Experiment 2, when the main effects of resource competition were examined in a manner that was unconfounded with compatibility, the only reliable effects were in the opposite direction from those predicted by resource competition, lesser competition was found with shared visual modalities.

Third, a number of analyses have examined the influence of S-C-R compatibility unconfounded by competition. This has been done across the two experiments in both single task conditions (in which timing artifacts may potentially influence the results) and in dual task conditions in which covariance analysis (Experiment 1) or decrement analysis (Experiment 2) was employed. Finally, the combined analysis of Experiments 1 and 2 indicated how strong and consistent were the combined effects of compatibility and competition when both were varied together. Moving across the top rows of Figure 2, practically all of the independent variables were influenced by either input or output compatibility of the fault task (see Table 4).

An overall summary of these analyses is shown in Table 5. Across the top of the table are represented the four major compatibility variables manipulated: input and output compatibility of the threat and fault task, respectively. Within each column of the table are shown the effects of the compatibility manipulations on the dependent variables: the threat task in the upper half, and the fault task in the lower half. Each entry within the table is a pair of symbols in parentheses. The first symbol of the pair represents the influence on latency, the second the influence on accuracy. A "+" indicates that low compatibility exerted an expected effect (increasing latency or error rate); a "." indicates no effect, and a "-" indicates an unexpected effect in which higher compatibility produced worse performance. There are several symbol pairs within the table. Those within the box are single task effects from Experiments 1 and 2. Those outside are dual task effects in Experiment 1 (E1), Experiment 2 (E2), and in the combined analyses of both (EB).

Finally, only those interactions that were reliable are shown, indicated by a bracket connecting two columns. These fall into two categories: a "+" indicates a "positive interactions": Making one variable incompatible enhances the effect of compatibility of another variable; a "-" indicates an underadditive interaction in which incompatibility of one variable reverses effect of compatibility of ther other, so that incompatible levels now yield better performance.

Table 5

Summary of Experiment Results

	Independent Variables			
	Threat Compatibility		Fault Compatibility	
	Input	Output	Input	Output
Threat Measures	E1 (++) E2 (++) E1 (·+) E1*(··) E2(·+) EB(·+)	E1 (+·) E2 (+–) E1*(··) (+·)	E1 (··) E2 (+·) EB (+·)	(+·) (++)
Fault Measures	E1 (++) E1*(+·) E2 (+·) (+ EB (++)	E1*(··) ·) (+·)	E1 (··) E2 (··) (– E1 (·+) E2 (– EB (+·) (·	·) E2 (–·) ·) (+·) +) (++)

E2 (+ ·)

*Test in which resource competition was pitted against compatibility.

Within each parentheses
(speed, accuracy)

+ = expected compatibility effect
· = no effect
- = effect in the opposite direction predicted by compatibility

E1 = Experiment 1
E2 = Experiment 2
EB = combined results of both experiments in between-subjects analysis
( ) that goes across a variable boundary indicates an interaction. "+" means a positive interaction. One compatibility variable is more pronounced at the incompatible level of the other variable.

Threat input . It is apparent from Table 5 that the effects of input compatibility were robust. The compatible visual threat display consistently showed better performance as assessed by speed or accuracy or both. This was true whether single or dual task performance was measured and, in the latter case whether performance decrements were measured on the threat or the fault task. The latter fact is particularly important because this is an effect that cannot be attributed to timing differences between the display modalities, but rather to the greater resource demands of the incompatible display. The robustness of the threat display compatibility effect is reflected in the contrast conducted in Experiment 1 in which the compatible configuration was also subject to greater resource competition, relative to the incompatible auditory condition (the * effect). Threat performance was unaffected, but fault latency was driven by the compatibility variable.

Fault input. The effect of input compatibility of the fault task was less pronounced, but still unambiguous. While single task results in both experiments showed no harmful main effects of the incompatible visual display, these effects were evident in decrement measures of threat latency (Experiment 2 and combined analysis), fault accuracy (Experiment 1), and fault latency (combined analysis). Furthermore, in Experiment 2 the harmful effects of display incompatibility on fault latency enhanced effect of threat compatibility.

Output compatibility. Output compatibility effects were somewhat less pronounced than those of input compatibility. For the threat task, the compatible manual response did consistently lead to more rapid performance and smaller performance decrements, than the speech response, although in the single task conditions of Experiment 2 this was accompanied by a decrease in accuracy. For the fault task the compatibility results were again equivocal. Here, decrements in both the latency measures of both tasks supported the compatibility interpretation. They were larger when the response was manual than when it was spoken. This was also true of the fault accuracy measure in the combined analysis, although as noted, this may have been the result of a difference between the two groups of subjects. However, contrary to the compatibility concept, fault task performance was slower (but just as accurate) with the speech response. Furthermore, the interaction between fault input and output compatibility on the latency measure was one of the following counter-intuitive form: making the fault display compatible (auditory) helped performance when the response was compatible, but <u>hurt</u> performance when the response was incompatible. STATED in other terms, the decrement in the TPO was exceptionally great when the fault task was displayed auditorily and responded to manually (independent of the modality of the threat display).

There seems to be no doubt that S-C-R compatibility effects operate on the tasks investigated here of greater cognitive complexity than those examined by Sandry and Wickens (1982). The main effects are of course moderated in some cases by interactions, relating in part to physical constraints on input and output (i.e., the "auditory overload" effect that was described).

A review of the results indicates that input compatibility effects were, in general, somewhat more pronounced than those of output compatibility. Two possible reasons may be proposed as to why this is the case. (1) For the threat task in particular, the cognitive demands of processing the input were quite a bit greater than those of selecting and executing the response (three simple alternatives). If input complexity is greater than output complexity, it stands to reason that input compatibility should be more potent than output.

(2) Elsewhere (Wickens & Sandry, 1983) we have indicated that C-R compatibility will be most pronounced in dual task conditions. This is because in single task conditions a C-R compatible response assignment will be one in which a given code of processing is responsible for both central processing and response activities, i.e., the verbal processor will be responsible for both the memory of fault information and for executing the speech responses. This situation could create a heavy demand on verbal resources that could neutralize C-R compatibility effects. Accordingly, we expect to find C-R compatibility advantages emerging only to the extent that time-sharing is going on. In the present experiment, there was some degree of time-sharing. However, the self-paced nature of the fault task probably made it relatively easier to adopt a serial processing strategy in which fault responses were given in the intervals between threat stimuli. This option lessened the amount of true time-sharing and hence the magnitude of C-R comaptibility effects.

This fact leads to the following general guideline: C-R compatibility will be of most importance only in those situations in which task constraints truly force a degree of parallel information processing. This is the case whenever a task is time-shared with continuous manual control (i.e., Sandry & Wickens, 1982, study). It is less likely to be the case when two discrete tasks are time-shared and one or both are self-paced.

Finally, it will be noted that in Sandry and Wickens' study we emphasized the need to consider the level of dual task performance, and not just the magnitude of dual task decrements. Yet in the present investigation, decrements were the primary variable of interest. We chose to examine decrements here primarily because, for the self-paced fault task, the speech recognition device placed severe mechanical constraints on the speed of performance. We believe that these constraints are in a sense artificial when latency is used as a dependent variable. They bias any estimates of human processing efficiency and presumably will be greatly reduced with future technological developments in speech recognition.

Future directions. The present data suggest that the focus of our future work on S-C-R compatibility will be on the S-C component. In future research we will be considering a greater range of tasks and display formats. In particular we will examine situations in which the tasks, unlike those used here are to some degree cross-coupled or correlated. The success of our predictions of S-C-R compatibility observed here, using the tasks of higher cognitive complexity suggest that the compatibility concept will continue to provide a useful guideline for system design.

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